Smart Patch System (SPS) for Condition Based Maintenance of Rotorcraft Structures

001 Development, Validation, and Demonstration of HUMS Technologies to Detect Cracks and Damages in Rotorcraft Structures and Dynamic Components

Contract # DTFACT-05-C-00022

Review Meeting, February 2007

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Project goals

- Develop a Smart Patch System (SPS) that can be used for the in-service monitoring of the health of new and existing rotorcraft structures.
- Provide data for certification of the system for rotorcraft structures as per AC29-2C Section MG-15
- Overall Goals of the system will be to:
  - Reduce the total structural inspection costs for rotorcraft structures
  - Avoid structural failure and catastrophic failures
  - Provide maintenance credit by reducing the number of maintenance activities when the structural condition assessment shows no need of the scheduled work.

SPS Certification Approach

Declare Application Intent
- Select airframe application(s)
- Determine how application(s) adds to, replaces, or intervenes in maintenance practices or flight operations
- Develop SPS design and installation requirements

Determine Criticality
- Perform Functional Hazard Assessment (FHA) to determine end-to-end criticality
- Establish criticality level and integrity criteria
- Document FHA

Develop SPS Design
- Design and optimize sensor layer
- Integrate with rotorcraft component
- Develop diagnostic algorithms and software
- Design on-aircraft hardware for integration with rotorcraft

Perform Coupon Tests
- Determine Probability of Detection (POD)
- Assess failure/degradation mechanisms
- Determine sensor reliability

Perform Rotorcraft Component Testing
- Evaluate Probability of Detection (POD) for component
- Assess SPS system Reliability
- Determine HUMS data interface

Continue

SPS Certification Approach

Continued

Evaluate Required Mitigation Actions

- Evaluate SPS performance
- Evaluate hardware and software qualification methods
- Determine any certification limitations

Develop Direct Evidence for System Validation

- Perform simulated flight testing
- Perform on-aircraft trials
- Perform flight testing as opportunities become available
- Perform “seeded tests” on-aircraft *if* opportunities become available

Develop Implementation and Technology Transfer Plans

- Develop Instructions for Continued Airworthiness (ICA)
- Develop plan for controlled introduction to service
- Develop training program
- Write certification compliance report

Project Information

- 5 year program
- Currently in Year 2 of project

<u>Team:</u>

- Acellent
- Sikorsky (contract to be finalized)
- Stanford University

Tasks

Task 1: Detailed workplan

Task 2: Reports

Task 3: Smart Patch System design

Task 4: Damage detection software

Task 5: Reliability issues

Task 6: SPS system testing and validation

Task 7: Implementation and technology transfer plan

Tasks worked on in the past 6 months

Task 1: Detailed workplan

Task 2: Reports

Task 3: Smart Patch System design

Task 4: Damage detection software

Task 5: Reliability issues

Task 6: SPS system testing and validation

Task 7: Implementation and technology transfer plan

- **Task 1:** Detailed workplan
- **Task 2:** Reports
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- **Task 7:** Implementation and technology transfer plan

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Detailed workplan

Submitted modified workplan at end of first year

Modifications include the following
- Focus on substantiation of certification procedures contained in AC-29-2C, Sec. MG-15 for usage credit

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Reports

Reports submitted on time:

- Annual report
- Monthly reports

- **Task 1:** Detailed workplan
- **Task 2:** Reports
- **Task 3:** Smart Patch System design
- **Task 4:** Damage detection software
- **Task 5:** Reliability issues
- **Task 6:** SPS system testing and validation
- **Task 7:** Implementation and technology transfer plan

Smart Patch System

- Smart patch system design
  1. Smart Patch
  2. Hardware
  3. Damage detection software
- Identification of rotorcraft components
- Functional Hazard Assessment (preliminary)

- **Task 1:** Detailed workplan
- **Task 2:** Reports
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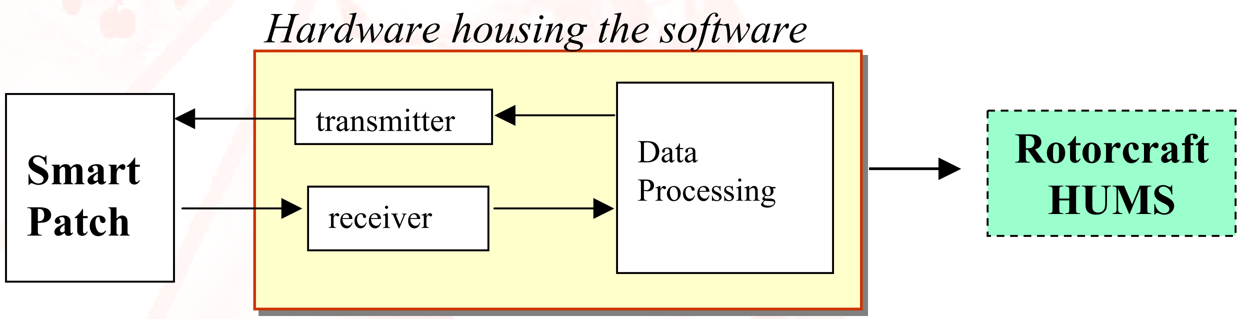
Smart Patch System



- **Smart Patch:** The smart patch is a network of piezoelectric transducers, each can be used as an actuator or a sensor
- **The Transmitter.** The transmitter is used to send the exciting signal to the actuator.
- **The Receiver.** The receiver is used to receive the signal read by the sensor.
- **Data Processing**. The data processing unit performs data storage and data analysis tasks. When the SPS is first installed, a set of baseline data is collected while the component is in good health. The analysis phase of data processing compares the newly collected data against the baseline data. The output of the data analysis is a report of the condition (health) of the component

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Smart Patch System design process

Smart Patch

- Sensor design
- Sensor layout
- Optimization
- Installation
- Protective coatings
- Reliability
- Survivability

Damage detection software

- Fatigue crack detection algorithms
- Quantification
- Self-diagnostics
- Environmental compensation
- User interface
- Data management
- Output

Hardware

- DAQ hardware
- Connectors and cables

System

- POD
- Integration
- Usage/training

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Smart Patch System design process

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System

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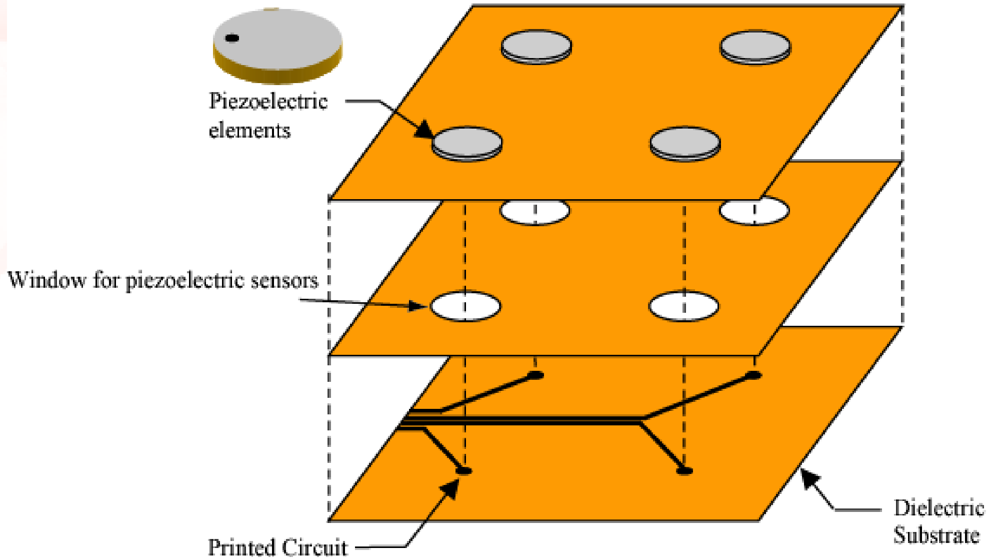
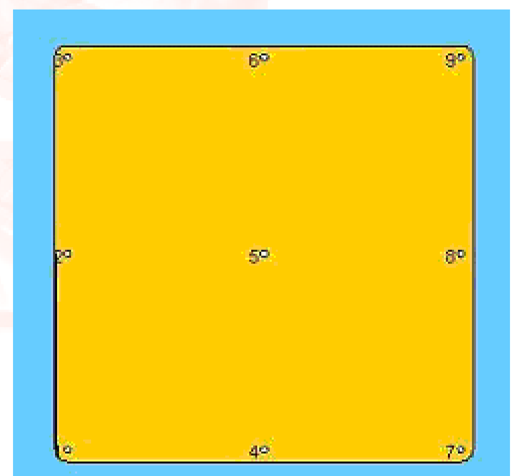
- Integration
- Usage/training

Smart patch design

- **Task 3:** Smart Patch System design
  - Smart Patch system design
  - Identification of rotorcraft components
  - Functional Hazard Assessment



Example of Smart Patch



- **Task 3:** Smart Patch System design
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Piezoelectric transducers

- PZT - lead-zirconate-titnate
- Piezoelectric single crystal

Typical sizes selected

- Disc shaped
  - 10 mil thick 0.25”dia
  - 30 mil thick 0.25” dia
  - 20 mil thick 0.1”dia
- Rectangular
  - 10 mil thick

PZT

PZT Material:	
Relative Dielectric Constant	
K^T	1250
Dielectric Dissipation Factor (Dielectric Loss (%)*	
tan δ	0.4
Curie Point (°C)**	
T_c	325
Electromechanical Coupling Factor (%)	
k_p	0.59
k_{33}	0.72
Piezoelectric Voltage Constant (10^{-3} Vm/N or 10^{-3} m^2/C)	
g_{33}	26.5
$-g_{31}$	11
g_{15}	38
Young's Modulus (10^{10} N/m^2)	
Y^E_{11}	8
Y^E_{33}	6.8
Frequency Constants (Hz*m or m/s)	
N_L (longitudinal)	1524
N_T (thickness)	2005
N_P (planar)	2130
Density (g/cm^3)	
ρ	7.6
Q_m	500

To be used if area where the transducers are to be mounted experience strain of <0.15%

Single crystal

Property	TRS-X2B
Composition	PMN-30%PT
Dielectric, K_3^T	5500-7500
Loss (tanδ)	<0.01
T_{RT} (1 kHz, °C)	85
d_{15} (pC/N)	2500-4000*
k_{33}	0.90
k_{31}	0.51
k_t	>0.55
N_{33} (Hz-m)	599
N_{31} (Hz-m)	721
N_t (Hz-m)	2002
Density (g/cm^3)	8.0

To be used if area where the transducers are to be mounted experience strain >0.15% - 1%

- **Task 3:** Smart Patch System design
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•The sensor placement depends on the distance that a signal can travel in the component. The farther a signal can travel, the farther apart the sensors can be placed. Parameters that can affect the signal traveling distance include the following:

- The property of the material of the component
- The structure of the component, such as if there are stiffeners or joints.
- The thickness of the material.
- The frequency of the signal
- The strength of the signal

•Sensor optimization considers three parameters:

- The structure of the component
- The critical damage size
- The signal traveling distance

Simulation software for sensor layout with Stanford has been developed

- **Task 3:** Smart Patch System design
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Identification of rotorcraft components for SPS system application

On-going work with Sikorsky

Objective: Select components for demonstration of SMART Patch System

Approach

- Review rotorcraft component families on airframe and dynamic systems.
- The assessment shall consider structural criticality, fatigue sensitivity, complexity, sensor feasibility, component testability, component availability, and benefit
- Generic component data shall be collected on the selected PSE(s) to aid in the demonstration

Milestone:

- 3/30 Component Selection

Key Component Selection Criteria

- **Task 3:** Smart Patch System design
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- Structural Criticality and Fatigue Sensitivity - Evidence that site has potential for crack in laboratory testing. Significance of the component to maintaining safety

- Complexity – Challenges in understanding loading, fatigue behavior, geometry features that influence demonstration results. Higher complexity for rotating components and complex joints.

- Benefit - Inspectability is low (requires more than walk around). Monitoring would allow reduced inspection and repair cost

- Feasibility for Damage Detection - Determine feasibility to apply sensor system to detect damage in laboratory and projected service aircraft.

- Component Availability and Testability in Laboratory Environment – Limit to planned ground test evaluations in order to leverage existing fatigue testing.

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Sample Evaluation Criteria

History
- Prevalence
- Cost of Repair
- Impact on availability

Complexity (low to high)
- Geometric (e.g, # of details/fasteners)
- Loading
- Certainty of BCs during operation

Inspectability (low to high)
- Walk Around
- At-aircraft maintenance inspection
- Teardown

Primary damage drivers
- Fatigue – LCF vs HCF
- Overstress (e.g., hard landings)
- Critical crack size

Repair Data
- Type of Fix
- Importance of early detection

Testability (low to high)

Availability of Analytical Results
- Loads Model
- Detail Model
- Fatigue Loads

Damage Detection Feasibility

Component Description

- **Task 3:** Smart Patch System design
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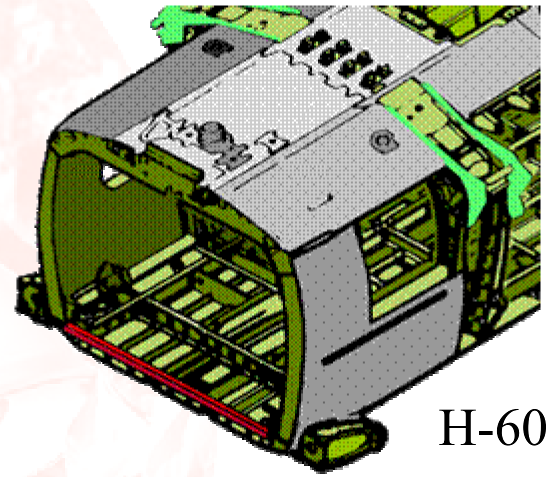
Airframe Elements

- Frame
- Frame (Upper Deck)
- Bulkhead
- Beams/Spars
- Stringers
- Skins
- Attachments/Lugs



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Dynamic Components

- MR and TR Blade/Spar
- MR Hub, Cuff and Yoke
- Transmission
- TR Hub and Horn
- Control System

Example Components

- **Task 3:** Smart Patch System design
  - Smart Patch system design
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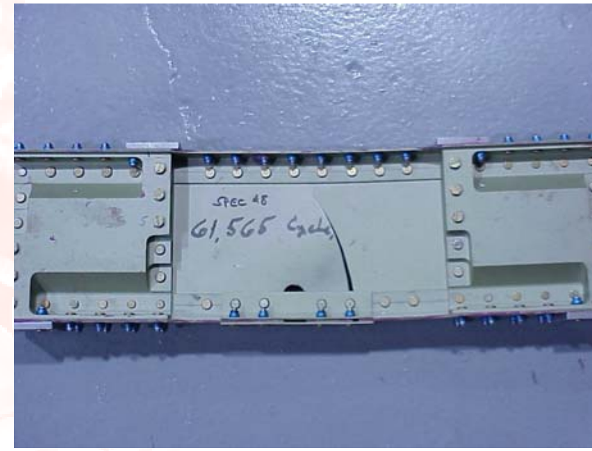
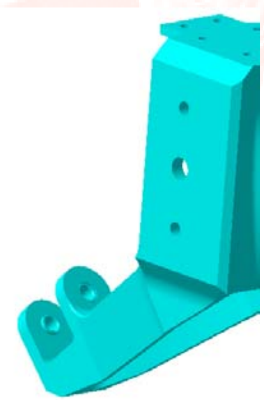
Airframe Elements

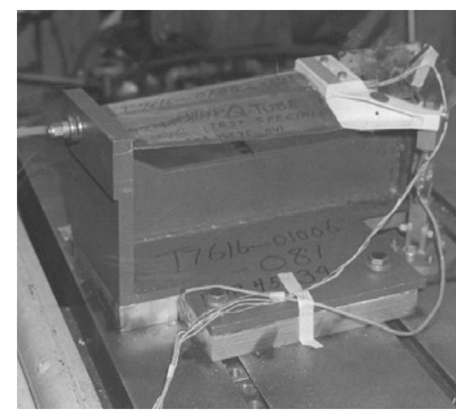
- Example case, Beam
- Metallic Component (Aluminum)
- Built-up Assembly with fasteners, and joints
- Early detection prevents major repair



Dynamic Component

- Example case, TR Horn
- Metallic Component (Aluminum)
- Tail Rotor Blade Attachment
- Low Complexity in Features
- Testing planned in 2007





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Functional Hazard Assessment

FHA components

Effect on rotorcraft

✓ Effect on SPS system

✓ Effect on SPS system components

Completed and submitted preliminary FHA to FAA

Functional Hazard Assessment

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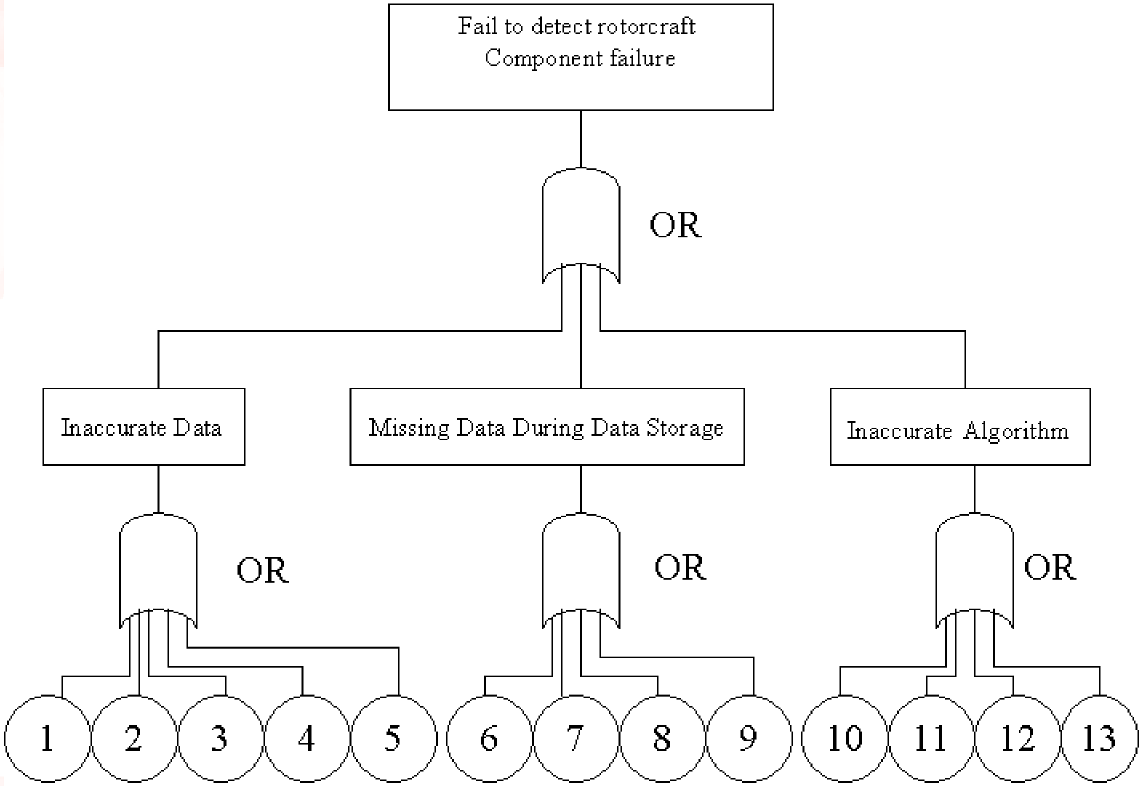

1 - Actuator or sensor wired to incorrect channel
2 - Actuator or sensor wiring failure
3 - Actuator or sensor degradation
4 - Transmitter failure – incorrect signal
5 - Receiver failure – incorrect signal
6 - Transmitter failure – no signal
7 - Wiring failure – no signal
8 - Receiver failure – no signal
9- System failure
10 - Software requirements incorrect
11 - Software design incorrect
12 - Coding errors
13 - Testing

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Functional Hazard Assessment

Criticality definitions from AC-29-2C, Sec. MG-15

Criticality (1309): This term describes the severity of the end result of a HUMS application failure/malfunction. Criticality is determined by an assessment that considers the safety effect that the HUMS application can have on the aircraft. There are five criticality categories as follows:

(i) Catastrophic

Failure conditions, which would prevent continued safe flight and landing.

(ii) Hazardous/Severe Major

Failure conditions, which would reduce the capability of the aircraft or the ability of the crew to cope with adverse operating conditions

(iii) Major

Failure conditions which would reduce the capability of the aircraft or the ability of the crew to cope with adverse operating conditions to the extent that there would be, for example, a significant reduction in safety margins or functional capabilities, a significant increase in crew workload or in conditions impairing crew efficiency, or discomfort to occupants, possibly including injuries.

(iv) Minor

Failure conditions which would not significantly reduce aircraft safety, and which would involve crew actions that are well within their capabilities. Minor failure conditions may include, for example, a slight reduction in safety margins or functional capabilities, a slight increase in crew workload such as routine flight plan changes, or some inconvenience to occupants.

(v) No-Effect (Non-hazardous class)

Failure conditions which do not affect the operational capability or safety of the aircraft, or the crew workload.

Functional Hazard Assessment

No.	Component	Function	Failure Mode	Failure Cause	Failure effect on SPS System	Failure detection method	Criticality level	Mitigation
SPS System								
SPS1	Actuator or sensor connection with hardware	Wiring for data transfer between sensors/actuators and hardware	incorrect data	actuator/sensor wired to incorrect channel in hardware	Incorrect data	Wiring QA procedure to check that each sensor and actuator is connected to the correct channel	Major	Each sensor or actuator will be assigned a unique channel number. A first detection of incorrect channel assignment is to check if a channel number is assigned more than once.Once an incorrect wiring is detected, the wire will be redone. After all wirings
SPS2	System	Data acqusition, storage and processing	Missing data	Power failure, hardware failure, operating system freeze and file system full	System will stop responding to user.	Torubleshooting for detection of failure methods	Minor	Manuals for troubleshooting of system failure will be created. Once the problem is fixed, the system should be tested for data acqusition.
SPS3	Data Storage	Data acquired from the system is stored in the hard drive for processing	Missing data	Loss due to hard drive failure	Loss of stored data		Minor	Data backup system will be established at a predefined schedule

Functional Hazard Assessment

No.	Component	Function	Failure Mode	Failure Cause	Failure effect on SPS System	Failure detection method	Criticality level	Mitigation
Smart patch								
s1	Piezo element	Sends and receives strain waves	Generation of voltage when strained		Electromagnetic interference	Pre-installation testing	Minor	Connector cover may short all piezos to mitigate this effect
			Cracking and/or depolarization	Exceeding failure strain from flight loads	Piezo loses function, Reduced system capability	Functional check prior to data collection using self-diagnostics	Minor	
				Mishandling			Minor	
				Impact from external object (debris, installation/removal of landing gear leg)			Minor	
			Disbonding from structure		Reduced sensitivity, reduced system capability	Visual inspection of sensor layer or measure sensor impedances	Minor	
s1	Kapton substrate	Provides support for sensors and sensor wiring	Degradation	Environmental exposure (hydraulic fluid, JP4, JP8, grease, moisture, high wind)	Loss of layer integrity,Loss of system	Visual inspection of sensor layer	Major	Use protective coating
s3	Wiring printed on kapton	Carries electrical signals from connector to sensors	Wire breakage	Overstrain	Reduced system capability	Functional check prior to data collection using self-diagnostics	Minor	
				Impact from external object (debris, installation/removal of landing gear leg)	Reduced system capability		Minor	
s4	Adhesive bond between Kapton and structure	Attaches sensor layer to structure	Disbond	Impact from external object (debris, installation/removal of landing gear leg)	Detachment of Kapton from structure, Loss of system	Visual inspection of sensor layer	Minor	Qualified adhesives will be used.
			Degradation, weak bond	Environmental exposure (hydraulic fluid, JP4, JP8, grease, moisture, high wind)	Detachment of sensor layer from structure, Loss of system		Minor	Improper surface preparation could lead to this condition and premature failure. Inspect for bond condition at each data collection.
s5	Copper shielding layer	Reduces crosstalk between actuators and sensors and reduces EMI from environment	Material degradation due to corrosion	Environmental exposure (hydraulic fluid, JP4, JP8, grease, moisture, high wind)	Increased crosstalk between actuator and sensors and increased environmental EMI,Reduced system capability		Minor	Use protective coating
			Shorting to wiring	Impact from external object (debris, installation/removal of landing gear leg)			Minor	
s6	Electrical connector	Provides location for connecting to external data acquisition equipment	Pins bending	Misuse (improper connector installation)	Loss of capability to collect data.	Visual inspection of connector prior to data collection	Minor	Training procedures will be in place. Rebending pins should not be difficult. Alternate design could use receptacles on layer.
			Filling with debris	Environmental exposure (hydraulic fluid, JP4, JP8, grease, moisture, high wind)	Connector requires cleaning before use	Visual inspection of connector prior to data collection	Minor	An environmentally sealed connector cover will be required.

Functional Hazard Assessment

No.	Component	Function	Failure Mode	Failure Cause	Failure effect on SPS System	Failure detection method	Criticality level	Mitigation
Hardware								
H1	Transmitter	Used to send excitation signal to the actuator	sending incorrect exciting signal	transmitter failure?		Visually verifying excitation signal	Minor	Methods for replacing transmitter will be in place. Software for comparision of a signal transmission pattern
			not sending exciting signal at all	transmitter failure?				
H2	Reciever	Used to recive the signal read by the sensor	receiving incorrect sensor signals			Visulization of missing senor signals and self-diagnostics. System will show	Minor	Methods for replacing reciever will be in place. A test package consisting of a damage free component that can
			not receiving any signal at all					

Functional Hazard Assessment

No.	Component	Function	Failure Mode	Failure Cause	Failure effect on SPS System	Failure detection method	Criticality level	Mitigation
Software								
w1	Software requirements for crack detection	Requirements for software development		Incorrect requirements		Software development document	Minor	Software requirements/specifications will be documented in the System Requirement Document. The document will be used to track the software development process
w2	Damage detection software design	Design for damage detection software		Incorrect design		Software design document	Major	Software design will be docuemnted in the Software Design Document and will be reviewed against the software requirements.
w3	Coding	Coding of developed software for damage detection		Coding errors by engineers			Minor	Indiivisual engineers will implement modules in the software design document and unit test the modules aginst the design. The complete implementation will then be integrated and tested for compliance with the design
w4	Testing	To ensure that all software requirements are implemented correctly.	Incorrect testing of software for functioning					A testing plan will be developed. The test plan will be excecuted by an independent test team. Any errors discovered during the testing phase will be fed back to the engineer team for fixing. The test will be repeated till no errors are found.

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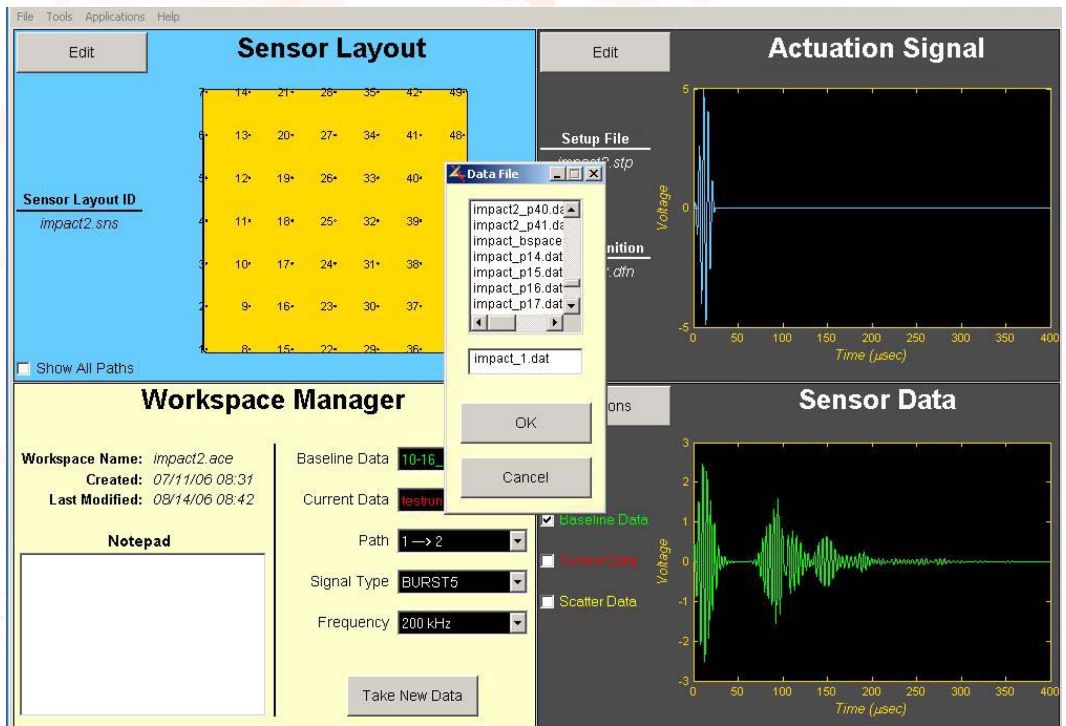
Data management software

Completed data management software for

- Data acquisition
- Sensor layout
- DAQ setup



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Testing

Worked on

- Coupon test plans *(ongoing)*
  - collected/summarized relevant data from previously conducted testing
  - developing tests plans for missing elements
- Component test discussions
- Flight test discussions

Goal for coupon tests

- Ensure sensor survivability
- Ensure that clean/usable data can be obtained

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Coupon tests

Previously conducted tests

Fatigue tests

- Steel, AL, Ti materials
- Sensor survived > 13,000 cycles

Temperature tests

- Sensor operational range -321°F to 340 °F

Vibration tests

- Steel material
- ±500με at 30 Hz

Moisture and salt fog

- Successfully survived MIL STD 810F tests

Sensor survivability has been proven

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Coupon tests

Previously conducted tests

Usable data collected for

- Lap joints
- Bonded joints
- Stringers
- Thick plates (upto 1.5”)
- Complex geometries

For rotorcraft structures the following tests are missing

- Data during dynamic testing
- Signal transfer in bolted joints

Test plans for both are currently being developed

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Component and flight tests

Component

- Component testing is being discussed with Sikorsky
- Candidate component is TR horn

Flight tests

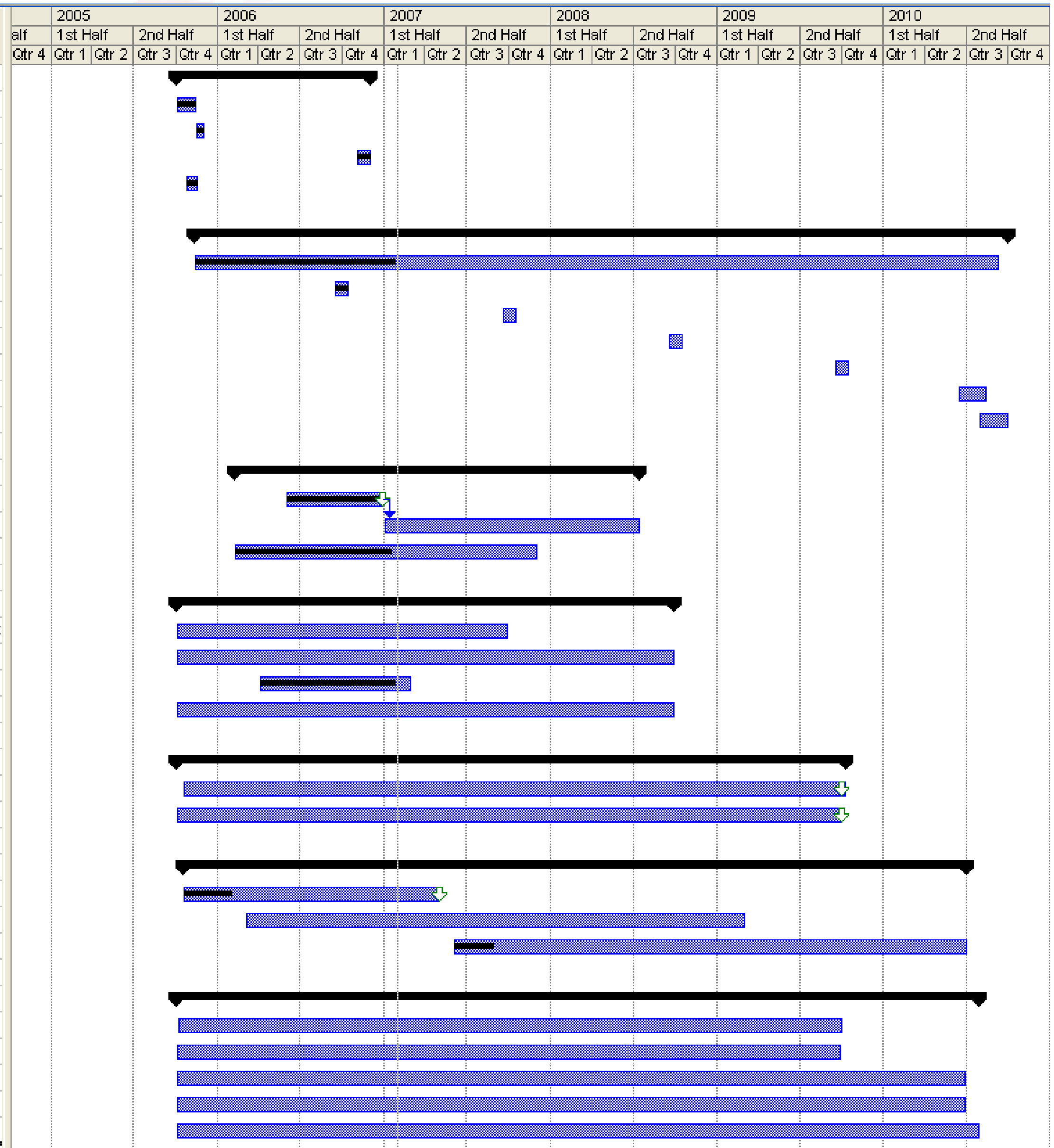
- Investigated working with RASCAL program at NASA Ames for flight tests
- Awaiting FAA-Army HUMS flight test set-up

Other

- Interested in finding out more about the test facility that FAA is building and if we may be able to work our system with it

Schedule

Task Name
Task 1: Detailed Workplan
Detailed work plan-draft
Detailed work plan-final
Revised workplan
Detailed workplan presentation
Task 2: Reports
Monthly status reports
Annual Technical report - yr1
Annual Technical report - yr2
Annual Technical report - yr3
Annual Technical report - yr4
Draft final technical report
Final technical report
Task 3: Smart Patch System Design
Functional Hazards assesment report - Preliminary
Functional Hazards assesment report - Final
SPS system design
Task 4 Damage detection software
Diagnostic software to detect damage its location and siz
Compensation for Enviromental conditions
Data management software
Software integration for implementation
Task 5 Reliability issues
Probability of detection
Self-diagnostics
Task 6 SPS system testing and validation
Coupon level tests
Component level tests
Flight test plan
Task 7 Implementation and Technology Transfer Plan
Methodologies to calculate credits
Physics of proposed credits for maintainence
Certification Compliance report
Technology transfer plan
Training



Future work

Task 2: Reports

Task 3: Smart Patch System design

- Develop/finalize component identification criteria
- Continue FHA
- Continue Smart Patch System design

Task 4: Damage detection software

- Damage detection software requirements
- Damage detection software design for fatigue crack detection
- Algorithms for missing elements

Task 6: SPS system testing and validation

- Conduct coupon tests
- Component test planning

Budget and expenditures status

Total budget for FY 2007	= $207,000
FY 2007 Expenditures to date	= $35,472
Total Remaining in 2007	= $171,528

Issues and concerns

None at this time